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12 a. DISTRIBUTION / AVAILABILITY STATEMENT

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12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The possibility of enhancing the luminescence efficiency of Er ions embedded in a semiconductor was investigated by growing about forty erbium-doped InGaAs/GaAs and GaAs/AlGaAs multiple quantum well samples by molecular beam epitaxy. The idea was to enhance the semiconductor-to-erbium transfer by tuning the quantum-well transition energy to equal one of the erbium ion transitions. Although photoluminescence was seen up to room temperature, strong diffusion of erbium and interdiffusion of Ga and Al ions degraded the quantum wells and formed Er traps that differ by positions of fine structure lines, photoluminescence lifetimes, and temperature dependences. This approach to Er-doped LED's does not look promising.

Vertical-cavity surface-emitting laser structures were studied under a wide variety of structure parameters, temperatures, and excitation conditions. Significant achievements include: magnetoexciton quantum dots exhibit no phonon bottleneck that might inhibit quantum-dot lasing; record splitting-to-linewidth ratios of normal-mode-coupling microcavities at 4 and 300 K; demonstration that present-day microcavities are far from the quantum statistical limit that could exhibit entanglement needed for quantum computation and that their threshold-like crossover of the photoluminescence from the upper polariton is not boser action involving Bose condensation. Many of these results and the corresponding many-body theories developed by S. W. Koch et al. in Marburg/Tucson are included in a submission to Reviews of Modern Physics

14. SUBJECT TERMS
Vertical-cavity surface-emitting lasers; normal-mode coupling; exciton-polariton laser; boser; Bose condensation; semiconductor microcavities; entanglement

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FINAL PROGRESS REPORT

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Appendix A. Interim Progress Report for 01 JAN 97 – 31 DEC 97.

Appendix B. Interim Progress Report for 01 SEP 95 - 31 DEC 96.

(4) Statement of the Problem Studied

The goal was to understand the physics relevant to the emission of light from semiconductors in order to reduce the threshold and improve the efficiency of vertical-cavity surface-emitting lasers (VCSEL's) and to improve the efficiency and directionality of light-emitting diodes (LED's). These devices are becoming increasingly attractive for optical interconnects and optical displays, making incremental improvements crucial. This was a synergistic program from the growth and study of materials and devices through the development of complete theories and computation of expected behavior.

(5) Summary of the Most Important Results

This research effort was in the physics part of the DARPA program with a goal of understanding and assessing phenomena potentially valuable in improving the efficiency and directionality of light emission from semiconductors. Since most of the ideas pursued were new and high risk, it is not surprising that many of them turned out to be overly optimistic. However, in the process of assessing those ideas much was learned that will affect future directions. And the ability of our Marburg/Tucson collaborators to compute these phenomena has progressed markedly during this contract driven in large part by the need to compute the phenomena we were studying.

Our most successful research during this contract was that on normal-mode coupling between one cavity mode and one exciton resonance in semiconductor microcavities. This culminated in the writing of a review article, "Nonlinear Optics of Normal-Mode-Coupling Semiconductor Microcavities," for Reviews of Modern Physics. [Khitrova et al.

99] This is a very interesting and controversial field where definitive experiments are essential to correct interpretations. Our principal contributions have been the following. Our growth of normal-mode-coupling microcavities with very large splitting-to-linewidth ratios made it possible to see new effects. We made a thorough study of both cw pump-probe and femtosecond transmission experiments and found a new nonlinear behavior: loss of transmission with little change in oscillator strength. [Jahnke et al. 96 & 97] Our nonlinear studies showed that present day microcavities are far from the quantum statistical limit, so their behavior can be explained semiclassically. Our thorough study of the emission properties of normal-mode-coupling microcavities as a function of incoherent excitation level and cavity-exciton detuning, showed that boser emission (Bose condensation followed by coherent emission) has not been seen yet. [Kira et al. 97] Finally, we made a thorough study of normal-mode-coupling reflectivity linewidths as a function of detuning. We found that the normal-mode-coupling linewidths can be understood completely using the quantum-well susceptibility deduced from measurements on bare quantum wells in a transfer-matrix computation of light propagation through the microcavity. [Ell et al. 98] These results are summarized in three Physical Review Letters.

Erbium Doping Destroys Quantum Wells and Generates Traps. The possibility of enhancing the luminescence efficiency of Er ions embedded in a semiconductor was investigated by growing about forty erbium-doped InGaAs/GaAs and GaAs/AlGaAs multiple quantum well samples by molecular beam epitaxy. The idea was to enhance the semiconductor-to-erbium transfer when the quantum-well and erbium-ion transition energies are equal. Photoluminescence of Er ions and Er induced defects was studied at liquid helium and higher temperatures. A strong diffusion of erbium and interdiffusion of Ga and Al ions was observed, leading at higher concentrations to the degradation of the quantum wells and macroscopic average leveling of the Er and Al concentrations over the whole grown structure. From high-resolution photoluminescence spectra the existence of three types of Er centers was deduced that differ by positions of fine structure lines, photoluminescence lifetimes, and temperature dependences. These centers cause three types of carrier traps with binding energies of 20, 50, and 400 meV. Evidence is given that carriers captured into these traps control the Auger excitation of Er ions assisted by multiphonon emission. Er luminescence associated with the 400 meV trap is still detectable at room temperature. This approach to Er-doped LED's does not look promising. [Gusev et al. 97]

Record Normal-Mode-Coupling Microcavities Are Still Far from the Quantum Statistical Limit. Research on semiconductor microcavities with a VCSEL-like structure with one or more narrow-linewidth quantum wells in the spacer field antinodes was much more rewarding. The record-narrow quantum-well linewidths also resulted in record ratios of the normal-mode-coupling splitting in reflection to the linewidth of the reflection dips. With the best normal-mode-coupling microcavities in the world, we were able to answer some fundamental questions. The appearance of new frequencies with increased excitation had been attributed to climbing a quantum ladder. By determining that the number of excitation photons that have to be absorbed to see changes in the transmission of a normal-mode-coupling microcavity is about 10^5, we determined that the best of present-day microcavities are far from the quantum statistical limit. In that limit, one should be able to entangle quantum states in a way that would be useful for factorization of large numbers by quantum computation. Just as it took atomic physicists more than a decade to reach that limit after first seeing normal-mode coupling, much work remains before semiconductor physicists will achieve it. [Wick et al. 96; Jahnke et al. 96; Gibbs et al. 97; Khitrova et al. 98 & 99]

Crossover of the Upper and Lower Polariton Photoluminescence Intensities Is Not Boser Action. When the single mode of a normal-mode-coupling microcavity is tuned slightly higher in energy than the exciton resonance of the quantum wells in its spacer, its photoluminescence following pulsed above-stopband excitation exhibits a curious effect. As the excitation energy increases, the upper polariton luminescence increases much faster than the lower polariton's; as a result, whereas at weak excitation the upper polariton's intensity is much weaker, it becomes much stronger. This threshold-like behavior and crossover of the intensities were attributed to boser action, i.e., coherent light emission following phonon-assisted Bose condensation into the upper branch. We conducted several definitive experiments. Comparison of cw transmission with the luminescence from both branches as a function of excitation level showed that the transmission is already single-peaked at crossover. Measurement of the normal-mode-coupling splitting versus excitation level revealed that the splitting has already collapsed to the detuning by crossover. Determination of the excitation level for lasing established that the lasing threshold density is only a factor of two above the crossover density. From these three experiments, we concluded that the crossover density is too high for boser action to be occurring. Many-body fully-quantized calculations show that the observations can be explained as electrons and holes recombining in a microcavity whose emission properties are affected strongly by the exciton absoption within its spacer. These measurements and computations do not rule out the possibility of boser action under more favorable conditions, but they show that the previous claims were wrong. [Kira et al. 97 & 98; Khitrova et al. 98 & 99; Gibbs et al. 97]

Quantum-Well Magnetoexcitons Do Not Exhibit a Phonon Bottleneck That Might Inhibit Quantum-Dot Lasing. Because the energy levels of quantum dots are discrete, it was suggested that electrons and holes might not be able to relax fast enough to provide gain for lasing. We tested for this so-called phonon bottleneck using pulsed excitation of quantum wells in a magnetic field; quantum-well confinement in the growth direction and magnetic field quantization in the plane result in discrete energy levels much like those of a quantum dot formed by 3D quantum confinement. We excited a VCSEL 150 meV above the exciton resonance (five times the optical phonon energy) and measured the delay in lasing as a function of magnetic field. The dynamics depend sensitively on excitation density and exciton-cavity detuning, but show no magnetic field dependence. Even at magnetic fields as high as 8 T, where the magnetoabsorption spectra exhibit deep and well-separated Landau levels, there is no increase in the time to maximum emission. These results hold over a wide range of carrier densities, from threshold to several orders of magnitude above threshold. The results evidence a fast relaxation which is uninhibited by the quasi-three-dimensional quantum confinement, indicating no phonon-bottleneck reduction of the carrier cooling rate. [Berger et al. 97]

Coherent Control of Microcavity-Laser Stimulated Emission. A curious aspect of the dynamics of our normal-mode-coupling samples relates to the spin precession of quantum-well electrons. Operating just above lasing threshold, we observe oscillations of the stimulated emission for circularly polarized excitation with an in-plane magnetic field B. The oscillations originate from gain modulation via the precession of the electron spin about the B axis. The oscillation frequency is twice the Larmor angular frequency $\omega_L = 2\pi g_e \mu_B B/h$, where g_e is the electron Landé g factor. The oscillation period of 40 ps corresponds to g = 0.45; the output oscillates between σ^+ and σ^- lasing. This oscillation is a form of coherent control, where the stimulated emission is synchronized to the spin precession of the electron. [Hallstein et al. 97]

(6) Publications

Publications (since last interim report except those marked with * as needed as references in report):

Aliev, G. N., N. V. Luk'yanova, R. P. Seisyan, M. R. Vladimirova, H. Gibbs, and G. Khitrova, "Exciton-Polariton Behavior of the Absorption Edge of Thin GaAs Crystals with the 'Super-Quantum' Thickness and MQW Enlarged Barriers," Phys. Stat. Sol. (a) **164**, 193 (1997).

Belousov, M. V., A. Yu. Chernyshov, I. V. Ignatev, I. E. Kozin, A. V. Kavokin, H. M. Gibbs, and G. Khitrova, "Statistical Model Explaining the Fine Structure and Interface Preference of Localized Excitons in Type-II GaAs/AlAs Superlattices," J. Nonlinear Optical Physics and Materials **7**, 13 (1998).

*Berger, J. D., S. Hallstein, O. Lyngnes, W. W. Ruhle, G. Khitrova, and H. M. Gibbs, "Emission Dynamics of a Magnetoexciton Quantum Dot Microcavity Laser," Phys. Rev. B **55**, R4910 (1997).

Ell, C., J. Prineas, T. R. Nelson, Jr., S. Park, H. M. Gibbs, G. Khitrova, S. W. Koch, and R. Houdré, "Influence of Structural Disorder and Light Coupling on the Excitonic Response of Semiconductor Microcavities," Phys. Rev. Lett. **80**, 4795 (1998).

Gibbs, H. M., D. V. Wick, G. Khitrova, J. D. Berger, O. Lyngnes, T. R. Nelson, Jr., E. K. Lindmark, S. Park, J. Prineas, M. Kira, F. Jahnke, S. W. Koch, W. Rühle, S. Hallstein, and K. Tai, "Nonlinear Semiconductor Microcavity Reflectance and Photoluminescence from Normal-Mode Coupling to Lasing," Festkörperprobleme-Advances in Solid State Physics **37**, 227 (1997).

*Gusev, O. B., J. P. Prineas, E. K. Lindmark, M. S. Bresler, G. Khitrova, H. M. Gibbs, I. N. Yassievich, B. P. Zakharchenya, and V. F. Masterov, "Er in MBE-grown GaAs/AlGaAs Structures," J. Appl. Phys. **82**, 1815 (1997).

Hallstein, S., J. D. Berger, M. Hilpert, H. C. Schneider, W. W. Rühle, F. Jahnke, S. W. Koch, H. M. Gibbs, G. Khitrova, and M. Oestreich, "Manifestation of Coherent Spin Precession in Stimulated Semiconductor Emission Dynamics," Phys. Rev. B **56**, R7076 (1997).

*Jahnke, F., M. Kira, S. W. Koch, G. Khitrova, E. K. Lindmark, T. R. Nelson, Jr., D. V. Wick, J. D. Berger, O. Lyngnes, H. M. Gibbs, and K. Tai, "Excitonic Nonlinearities of Semiconductor Microcavities in the Nonperturbative Regime," Phys. Rev. Lett. **77**, 5257 (1996).

Jahnke, F., M. Kira, S. W. Koch, G. Khitrova, and H. M. Gibbs, "Optical Nonlinearities of Quantum-Confined Excitons in Semiconductor Microcavities," Opt. Phot. News **8**(12), 39 (1997).

Khitrova, G., D. V. Wick, J. D. Berger, C. Ell, J. P. Prineas, T. R. Nelson, Jr., O. Lyngnes, H. M. Gibbs, M. Kira, F. Jahnke, S. W. Koch, W. Rühle, and S. Hallstein, "Excitonic Effects, Luminescence, and Lasing in Semiconductor Microcavities," Phys. Stat. Sol. (b) **206**, 3 (1998).

Khitrova, G., H. M. Gibbs, F. Jahnke, M. Kira, and S. W. Koch, "Nonlinear Optics of Normal-Mode-Coupling Semiconductor Microcavities," Reviews of Modern Physics, invited, revised version resubmitted (1999).

*Kira, M., F. Jahnke, S. W. Koch, J. D. Berger, D. V. Wick, T. R. Nelson, Jr., G. Khitrova, and H. M. Gibbs, "Quantum Theory of Nonlinear Semiconductor Microcavity Luminescence Explaining 'Boser' Experiments," Phys. Rev. Lett **79**, 5170 (1997).

Kira, M., F. Jahnke, S. W. Koch, J. D. Berger, D. V. Wick, T. R. Nelson, Jr., G. Khitrova, and H. M. Gibbs, "Quantum Theory of Spontaneous Emission from Microcavities," SPIE **3283**, 212 (1998).

*Wick, D. V., T. R. Nelson, Jr., E. K. Lindmark, H. M. Gibbs, G. Khitrova and K. Tai, "Semiconductor Microcavities in the Strong Coupling Regime," in *Proceedings of the SPIE—Physics and Simulation of Optoelectronic Devices IV*, SPIE Proceedings **2693**, 160 (1996).

Meeting abstract since last interim report:

Ell, C., J. Prineas, T.R. Nelson, Jr., S. Park, H.M. Gibbs, G. Khitrova, S.W. Koch, R. Houdré, "Disorder-Averaged Excitonic Response and its Application to Normal-Mode Coupling in Semiconductor Microcavities within a Linear Dispersion Theory", QTuG2, International Quantum Electronic Conference (IQEC'98), San Francisco, May, 3-8, 1998.

Ell, C., J. Prineas, T. R. Nelson, Jr., S. Park, E. S. Lee' H. M. Gibbs, G. Khitrova' S.W. Koch, R. Houdré, "Excitons and Excitonic Features in Microcavities and Multiple Quantum Well Bragg Samples", Ultrafast Phenomena in Semiconductors II (SPIE98), San Jose, January 26-30, 1998. Invited talk.

Gibbs, H. M., G. Khitrova, J. P. Prineas, E. S. Lee, C. Ell, and M. Hübner, "Radiative Broadening of Coupled Excitons in Quantum-Well Structures," XVI International Conference on Coherent and Nonlinear Optics (ICONO'98), Moscow, June 29 – July 3, 1998. Invited talk.

Gibbs, H. M., G. Khitrova, J. D. Berger, D. V. Wick, T. R. Nelson, Jr., S. W. Koch, M. Kira, and F. Jahnke, "Photoluminescence from a Normal-Mode-Coupling Semiconductor Microcavity," QTuA3, International Quantum Electronic Conference (IQEC'98), San Francisco, May, 3-8, 1998. Invited talk.

Gibbs, H.M., G. Khitrova, C. Ell, J. Prineas, T.R. Nelson, Jr., S. Park, S.W. Koch, and R. Houdré, "Influence of Structural Disorder and Light Coupling on the Excitonic Response of Semiconductor Microcavities," Italian-German International Symposium on Microcavities – Quantum Electrodynamics and Devices (193rd WE-Heraeus Symposium), Villa Vigoni, Loveno di Menaggio, Italy, April 5-8, 1998.

Gibbs, H.M., C. Ell, G. Khitrova, J. Prineas, T.R. Nelson, Jr., S. Park, E. Lee, R. Houdré, S.W. Koch, "Linewidths of Normal-mode-coupling Microcavities", Workshop on Radiatve Processes and Dephasing in Semiconductors, Coeur d'Alene, Idaho, February 2-4, 1998. Invited talk.

Gibbs, H.M., C. Ell, G. Khitrova, D.V. Wick, J.D. Berger, T.R. Nelson, Jr., M. Kira, F. Jahnke, S.W. Koch, "From Normal-Mode Coupling to Lasing: Photoluminescence from a Semiconductor Microcavity", Physics and Simulation of Optoelectronic Devices VI (SPIE98), San Jose, January 26-30, 1998. Invited talk.

Khitrova, G., H. M. Gibbs, J. D. Berger, D. V. Wick, and T. R. Nelson, Jr., S. W. Koch, M. Kira, and F. Jahnke, "Nonlinear Photoluminescence from a Normal-Mode-Coupling Semiconductor Microcavity," XVI International Conference on Coherent and Nonlinear Optics (ICONO'98), Moscow, June 29 – July 3, 1998. Invited talk.

Khitrova, G., "Photoluminescence from a Normal-Mode-Coupling Semiconductor Microcavity", Physics of Quantum Electronics '98: Invited talk.

Lee, Y.-S., A. Maslov, T. B. Norris, D. S. Citrin, J. Prineas, G. Khitrova, and H. M. Gibbs, Coherent Control of Normal Modes in Quantum-Well Semiconductor Microcavity," International Quantum Electronic Conference (IQEC'98 post-deadline QPD2), San Francisco, May, 3-8, 1998.

Prineas, J.P., E.S. Lee, C. Ell, H.M. Gibbs, G Khitrova, "Linear Spectra of Radiatively Coupled Excitons in InGaAs Quantum Well Structures", QFB7, International Quantum Electronic Conference (IQEC'98), San Francisco, May, 3-8, 1998.

(7) Scientific Personnel

Hyatt M. Gibbs, Professor, PI

Galina Khitrova, Co-PI, promoted from Assistant to Associate Professor during this contract period.

Claudia Ell, Research Assistant Professor, also received partial support from this contract.

Ove Lyngnes, Eric Lindmark, Tom Nelson, Dave Wick, and Jill Berger obtained Ph.D. degrees partially supported by this grant; the last four are US citizens. John Prineas, graduate student, was also involved with this research.

Approximately twenty scientists of the Ioffe Institute and the St. Petersburg State and Technical Universities have been supported by this grant. Especially involved in the Er luminescence studies were Gusev, Bresler, Yassievich, and Masterov. Zapasskii, who spent two seven-month periods in Tucson, worked with the superconducting magnet and with microcavity photoluminescence. Kavokin and Kaliteevski are young theorists who helped with exciton physics calculations, especially for magnetoexcitons. Belousov, Ignatev, Kozin, Zakharchenya, Dzhioev, Korenev, Tkachuk, and Ivchenko concentrated on interface physics studies. This contract and Soros helped these scientists survive to this point, but the future is grim; by the end of this contract it was becoming almost impossible to do good science in St. Petrsburg.

(8) Inventions

None.

(9) Bibliography

See **(6) Publications**.

Appendix A. Interim Progress Report for 01 JAN 97 – 31 DEC 97.

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5. FUNDING NUMBERS DAAH04-95-1-0612

6. AUTHOR(S)

Hyatt Gibbs & Galina Khitrova

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)

University of Arizona

8. PERFORMING ORGANIZATION REPORT NUMBER

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

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11. SUPPLEMENTARY NOTES

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12a. DISTRIBUTION / AVAILABILITY STATEMENT

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12 b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

InGaAs/GaAs quantum wells with record narrow linewidths less than 1 meV have been grown inside a semiconductor microcavity consisting of GaAs/AlAs distributed Bragg reflectors and a GaAs spacer. Vacuum Rabi splitting or normal mode coupling results because of the strong coupling between these two oscillators, namely the exciton and the cavity mode. The quantum-well narrow linewidth and the high-finesse cavity result in record values of the splitting to linewidth ratio. This permitted the observation of a new nonlinear effect: with increased excitation the transmission of the coupled system goes to zero with negligible reduction in the splitting. Measuremnts on quantum wells outside the cavity reveal that at densities below the onset of state filling and bandgap renormalization the exciton broadens with little change in oscillator strength. By correlating the nonlinear transmission with the photoluminescence, it was established that the density is too high for excitons to behave as bosons when the upper polariton emission increases rapidly compared to the lower. This impressive crossover, called by some boser action and attributed to Bose condensation into the upper polariton, results instead from the recombination emission of fermions (electrons and holes) in a microcavity with a density dependent photon density of states. Emission studies as a function of temperature and sample parameters are planned.

14. SUBJECT TERMS

Vertical-cavity surface-emitting lasers, normal-mode coupling, exciton-polariton laser, boser, Bose condensation

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1. Publications in Refereed Journals

This list does not include many published abstracts of invited and contributed talks.

Aliev, G. N., N. V. Luk'yanova, R. P. Seisyan, M. R. Vladimirova, H. Gibbs, and G. Khitrova, "Exciton-Polariton Behaviour of the Absorption Edge of Thin GaAs Crystals with the 'Super-Quantum' Thickness and MQW Enlarged Barriers," Phys. Stat. Sol. (b), to be published (1997).

Belousov, M. V., A. Yu. Chernyshov, I. V. Ignatev, I. E. Kozin, A. V. Kavokin, H. M. Gibbs, and G. Khitrova, "Statistical Model Explaining the Fine Structure and Interface Preference of Localized Excitons in Type-II GaAs/AlAs Superlattices," J. Nonlin. Opt. Phys. Matl. to be published (1998).

Berger, J. D., S. Hallstein, O. Lyngnes, W. W. Ruhle, G. Khitrova, and H. M. Gibbs, "Emission Dynamics of a Magnetoexciton Quantum Dot Microcavity Laser," Phys. Rev. B **55**, R4910 (1997).

Dzhioev, R. I., H. M. Gibbs, E. L. Ivchenko, G. Khitrova, V. L. Korenev, M. N. Tkachuk, and B. P. Zakharchenya, "Linear-Circular Polarization Conversion under Optical Orientation of Excitons in Type-II GaAs/AlAs Superlattices," Phys. Rev. B **56**, 13405 (1997).

Gibbs, H. M., D. V. Wick, G. Khitrova, J. D. Berger, O. Lyngnes, T. R. Nelson, Jr., E. K. Lindmark, S. Park, J. Prineas, M. Kira, F. Jahnke, S. W. Koch, W. Rühle, S. Hallstein, and K. Tai, 1997, "Nonlinear Semiconductor Microcavity Reflectance and Photoluminescence from Normal-Mode coupling to Lasing," Festkörperprobleme/Advances in Solid State Physics **37**, ?? (1997).

Gusev, O. B., J. P. Prineas, E. K. Lindmark, M. S. Bresler, G. Khitrova, H. M. Gibbs, I. N. Yassievich, B. P. Zakharchenya, and V. F. Masterov, "Er in MBE-Grown GaAs/AlGaAs Structures," J. Appl. Phys. **82**, 1815 (1997).

Hallstein, S., J. D. Berger, M. Hilpert, H. C. Schneider, W. W. Rühle, F. Jahnke, S. W. Koch, H. M. Gibbs, G. Khitrova, and M. Oestreich, "Manifestation of Coherent Spin Precession in Stimulated Semiconductor Emission Dynamics," Phys. Rev. B **56**, R7076 (1997).

Jahnke, F., M. Kira, S. W. Koch, G. Khitrova, E. K. Lindmark, T. R. Nelson, Jr., D. V. Wick, J. D. Berger, O. Lyngnes, H. M. Gibbs, and K. Tai, "Excitonic Nonlinearities of Semiconductor Microcavities in the Nonperturbative Regime," Phys. Rev. Lett. 77, 5257 (1996).

Jahnke, F., M. Kira, S. W. Koch, G. Khitrova, and H. M. Gibbs, "Optical Nonlinearities of Quantum-Confined Excitons in Semiconductor Microcavities," Opt. Phot. News **8**(12), 39 (1997).

Kavokin, A. V., M. R. Vladimirova, M. A. Kaliteevski, O. Lyngnes, J. D. Berger, H. M. Gibbs, and G. Khitrova, "Resonant Faraday Rotation in a Semiconductor Microcavity," Phys. Rev. B **56**, 1087 (1997).

Khitrova, G., D. V. Wick, J. D. Berger, C. Ell, J. P. Prineas, T. R. Nelson, Jr., O. Lyngnes, H. M. Gibbs, M. Kira, F. Jahnke, S. W. Koch, W. Rühle, and S. Hallstein, "Excitonic Effects, Luminescence, and Lasing in Semiconductor Microcavities," Phys. Stat. Sol. (b), to be published (1998a).

Khitrova, G., H. M. Gibbs, F. Jahnke, M. Kira, and S. W. Koch, "Semiconductor Physics of Quantum Wells and Normal-Mode Coupling Microcavities," Reviews of Modern Physics, invited (1998b).

Kira, M., F. Jahnke, S. W. Koch, J. D. Berger, D. V. Wick, T. R. Nelson, Jr., G. Khitrova, and H. M. Gibbs, "Quantum Theory of Nonlinear Semiconductor Microcavity Luminescence Explaining 'Boser' Experiments," Phys. Rev. Lett **79**, 5170 (1997).

Kokhanovskii, S. I., K. Moumanis, M. E. Sasin, R. P. Seisyan, A. V. Kavokin, H. Gibbs, and G. Khitrova, "Coulomb-Well Effects in Magnetooptical Spectra of (In,Ga)As/GaAs Multiple Quantum Well Structures," Optics of Excitons in Confined Systems, Goettingen, August (1997).

Lyngnes, O., J. D. Berger, J. P. Prineas, S. Park, G. Khitrova, H. M. Gibbs, F. Jahnke, M. Kira, and S. W Koch, "Nonlinear Emission Dynamics from Semiconductor Microcavities in the Nonperturbative Regime," Solid State Commun. **104**, 297 (1997).

Nelson, Jr., T. R., J. P. Prineas, G. Khitrova, H. M. Gibbs, J. D. Berger, E. K. Lindmark, J.-H. Shin, H.-E. Shin, and Y.-H. Lee, "Room-Temperature Normal-Mode-Coupling in a Semiconductor Microcavity Utilizing Native-Oxide AlAs/GaAs Mirrors," Appl. Phys. Lett. **69**, 3031 (1996).

Ten, S., J. G Williams, P. T. Guerreiro, G. Khitrova, and N. Peyghambarian, "Ultrafast Excitonic Room Temperature Nonlinearity in Neutron Irradiated Quantum Wells," Appl. Phys. Lett. **70**, 158 (1997).

2. Participating Personnel and Advanced Degrees

Five students received PhD degrees during the last year partially supported by this grant: Eric Lindmark, Jill Berger, and David Wick in Optical Sciences; Ove Lyngnes and Tom Nelson in Physics. John Prineas, Sahnggi Park, and Euseong Lee are now working part time for this grant. Galina Khitrova was promoted to Associate Professor with tenure in 1997.

3. Inventions

None.

4. Scientific Progress and Accomplishments

a. Statement of the Problems Studied

IMPROVING VCSEL's AND RARE-EARTH-DOPED LED's

The goal is to understand the mechanisms important in the emission of light from semiconductors in order to reduce the threshold and improve the efficiency of vertical-cavity surface-emitting lasers (VCSELs) and to improve the efficiency and directionality of light-emitting diodes (LEDs). These devices are becoming increasingly attractive for optical interconnects and optical displays, making incremental improvements crucial. This is a synergistic program from the growth and characterization of materials and devices through the development of complete theories and computer codes.

b. Summary of the Most Important Results

Nonlinear Behavior of Normal Mode Coupling in Semiconductor Microcavities

We have grown InGaAs/GaAs quantum wells with very narrow linewidths (1 meV = 0.6 nm). By growing a single QW in the center of a one-wavelength GaAs spacer or two in the two central anti-nodes of a $3\lambda/2$ microcavity, we have observed record splitting-to-linewidth ratios (>10, showing that the narrow QW linewidths are also achieved within the microcavity spacer) of so called vacuum Rabi splitting at 4K. This phenomenon is also known as normal mode coupling (NMC) because it exhibits the characteristic anti-crossing curve of two coupled oscillators (here exciton and cavity) as their relative detuning is scanned through zero. We have increased the splitting, seen in reflectivity or transmission, by placing the microcavity in a magnetic field up to 12T, showing that the splitting depends linearly on the electric dipole moment. We have also seen record depth of modulation vacuum field Rabi oscillations because of the high quality of our samples.

We have studied the nonlinear transmission and reflection of our NMC microcavities both by cw pump/probe (Jahnke et al. 96) and by femtosecond reflection and upconversion (Lyngnes et al. 97). Because of our very narrow linewidths, we see a *new nonlinear behavior: the transmission drops to zero with almost no reduction in NMC*; this is explained by nonlinear dispersion theory using the measured exciton absorption with increased carrier density in a transfer matrix formalism. *The basic physics is exciton broadening before loss of oscillator strength*; as the exciton broadens the absorption increases at the detuned wavelengths of the NMC transmission peaks thus decreasing the Fabry-Perot transmission (a little bit of absorption in a high-finesse cavity destroys its transmission). Since the area under the exciton absorption (proportional to oscillator strength) changes very little as the broadening sets in, there is almost no reduction in splitting while the transmission drops to zero (Gibbs et al. 97). This curious nonlinear behavior could not be seen by other groups whose NMC samples were so inhomogeneously broadened that exciton broadening had little effect and loss of oscillator strength domintaed the nonlinear behavior. The cw nonlinear measurements and agreement with a many-body theory (with Stephan Koch, Frank Jahnke, and Mackillo Kira, Marburg, Germany) have been published in Physical Review Letters (Jahnke et al. 96) and Optics and Photonic News (Jahnke et al. 97). Since we measured that almost a million photons must be absorbed to drop the NMC transmission in half, we concluded that all present-day NMC experiments in semiconductors are very far from the quantum statistical limit.

Next we made extensive measurements on the photoluminescence spectra of NMC samples as a function of excitation density and correlated them with the nonlinear transmission. From such measurements and many-body calculations of the Bosonic commutator, we established that the rapid increase in the upper polariton emission relative to the lower polariton emission is not a result of Bose condensation or final state stimulation as proposed by others. Instead it is simply the emission of an excitation-dependent distribution of emitters within a microcavity whose photon density of states is also excitation dependent. Of course, the proper theoretical description of the PL, requiring quantization of the field self consistently with the nonlinear propagation effects within the microcavity, is a very difficult computational problem. The cw nonlinear PL measurements and agreement with a many-body theory (with Stephan Koch, Mackillo Kira, & Frank Jahnke, Marburg, Germany) have been published in Physical Review Letters (Kira et al. 97) with more details in Khitrova et al. 98a.

The measurements described so far were performed at 4K, but we have achieved better room-temperature normal-mode coupling than the first observation by Houdré using InGaAs/GaAs quantum wells in a microcavity with aluminum-oxide/GaAs mirrors (Nelson, Jr. et al. 96). These 300K observations suggest that once the physics of NMC microcavities is understood well at low temperatures, there may be some room-temperature applications. Our proposal seeks support to investigate some of these.

A comprehensive review of normal-mode coupling in semiconductor microcavities including our own work with the theory group of S. W. Koch will be published in Reviews of Modern Physics (Khitrova et al. 98b).

1.54-μm Photoluminescence from Erbium-Doped Quantum Wells

The possibility of enhancing the luminescence efficiency of Er ions embedded in a semiconductor was investigated by growing about forty erbium-doped InGaAs/GaAs and GaAs/AlGaAs multiple quantum well samples by molecular beam epitaxy. The idea was to enhance the semiconductor-to-erbium transfer when the quantum-well and erbium-ion transition energies are equal. Photoluminescence of Er ions and Er-induced defects was studied at liquid helium and higher temperatures both by our students in Tucson and by Misha Bresler, Oleg Gusev, Irina Yassievich, and Vadim Masterov in St. Petersburg who have many years experience on rare-earth doped semiconductors. We observed 1.54-μm photoluminescence at 4K from some of the InGaAs:Er/GaAs quantum wells, but found that it is very difficult to grow InGaAs/GaAs QWs reproducibly with a 980-nm transition energy at 4K. We had better success growing GaAs:Er/AlGaAs QWs in resonance with the 810-nm transition of Er^{3+}. We hoped that transferring energy to a higher lying level of the Er ion would stop the back transfer that is a problem for 300K operation. A strong diffusion of erbium and interdiffusion of Ga and Al ions was observed, leading at high erbium concentrations to the degradation of the QW's and macroscopic average levelling of Er and Al concentrations over the whole grown structure. From high-resolution PL spectra the existence of three types of Er centers was deduced which differ by positions of fine structure lines, PL lifetimes, and temperature dependence (Gusev et al. 97). These centers cause three types of carrier traps with binding energies of 20, 50, and 400 meV. Evidence was found that carriers captured into these traps control the Auger excitation of Er ions assisted by multiphonon emission. Er PL associated with the 400 meV trap was still detectable at room temperature. Although we learned some interesting physics of interdiffusion and traps, we like many before us failed to find a way to obtain transfer from an excited semiconductor to Er efficient enough to make a good light source.

Other Research Related to this DARPA/ARO Research

Work related to this DARPA/ARO project includes: no phonon bottleneck in a magnetoexciton quatum dot laser (already reported last year and now published in Berger et al. 97); spin-quantum-beat modulation of VCSEL emission (Hallstein et al. 97); QW femtosecond spectroscopy of fast recovery (Ten et al. 97); (physics and statistical model for GaAs/AlAs interfaces (Dzhioev et al. 97, Belousov et al. 98); magnetoexciton studies of enhancement of forbidden transitions by Coulomb-well effects (Kokhanovskii et al. 97) and resonant Faraday rotation in a microcavity (Kavokin et al. 97); and bulk polariton effects in finite-length crystals (Aliev et al. 97). Our unusually narrow-linewidth QWs and high-quality normal-mode coupling microcavities are now under study in several places around the world: Stuttgart (Kuhl); Marburg (Rühle); St. Petersburg (Belousov, Seisyan, Thachuk); Eugene, Oregon (Raymer); Lausanne (Houdré, Stanley); Paris (Giacobino); and Ann Arbor (Norris).

5. Technology Transfer

Our primary mechanisms for technology transfer are publications and talks and discussions at meetings. The annual DARPA Review offers an excellent opportunity for such discussions expecially via the new poster format. Also the COEDIP (Center for Optoelectronic Devices, Interconnects and Packaging) meetings each year at the University of Maryland and the University of Arizona are effective industry/university mixers.

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13. ABSTRACT *(Maximum 200 words)*
The nonlinear optical transmission and reflection of a semiconductor microcavity exhibiting record normal-mode-coupling have been measured by pump-probe techniques and explained by a first-principles theory. The new nonlinear behavior arises because of exciton broadening that occurs at higher densities and dominates over the inhomogeneous broadening of the very-narrow-linewidth quantum wells in the microcavity antinodes. With GaAs/native-oxide mirrors, the normal mode coupling is still well-resolved at room temperature.
Magnetoexcitons were studied to determine if carrier relaxation is a problem for these near-ideal quantum dots. The absence of any change in lasing following femtosecond excitation as the magnetic field is increased shows that relaxation is still quite rapid even if the quantum well continuum is broken up into Landau levels. If evidence had been found for a phonon bottleneck for magnetoexcitons, it would have implied similar problems for a quantum-dot laser.

14. SUBJECT TERMS
Semiconductor lasers. Vertical-cavity surface-emitting lasers. Rare-earth-doped emitters. Phonon bottleneck. Cavity QED.

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1. List of Manuscripts

T. R. Nelson Jr., E. K. Lindmark, D. V. Wick, K. Tai, G. Khitrova, and H. M. Gibbs "Normal-mode coupling in planar semiconductor microcavities," in J. Rarity and C. Weisbuch, eds., *Microcavities and Photonic Bandgaps: Physics and Applications* (Kluwer, 1996).

R. Jin, M. S. Tobin, R. P. Leavitt, H. M. Gibbs, G. Khitrova, D. Boggavarapu, O. Lyngnes, E. Lindmark, F. Jahnke, and S. W. Koch, "Order of magnitude enhanced spontaneous emission from room-temperature bulk GaAs," in J. Rarity and C. Weisbuch, eds., *Microcavities and Photonic Bandgaps: Physics and Applications* (Kluwer, 1996).

M. F. Krol, S. Ten, B. P. McGinnis, M. J. Hayduk, and G. Khitrova, "Ultrafast hole tunneling by nonresonant delocalization in asymmetric double quantum wells," Phys. Rev. B Rapid Communication **52** (20), 14344 (1995).

P. G. Baranov, N. G. Romanov, I. V. Mashkov, G. Khitrova, H. M. Gibbs, and Ove Lyngnes, "Local diagnostics of GaAs/AlAs superlattices using optically detected magnetic resonance and level anticrossing effect," Solid State Physics **37**, 1648 (1995).

J. Berger, O. Lyngnes, H. M. Gibbs, G. Khitrova, T. R. Nelson, E. K. Lindmark, A. V. Kavokin, M. A. Kaliteevski, and V. V. Zapasskii, "Magnetic field enhancement of the exciton-polariton splitting in a semiconductor quantum-well microcavity: beyond the strong coupling threshold," Phys. Rev. B **54**, 1975 (1996).

E. K. Lindmark, T. R. Nelson, Jr., G. Khitrova, H. M. Gibbs, A. V. Kavokin, and M. A. Kaliteevski, "Three coupled oscillators: normal mode coupling in a microcavity with two different quantum wells," Opt. Lett. **21**, 994 (1996).

A. V. Kavokin, M. A. Kaliteevski, S. V. Goupalov, J. D. Berger, O. Lyngnes, H. M. Gibbs, G. Khitrova, A. Ribayrol, A. Bellabchara, P. Lefebvre, D. Coquillat, and J. P. Lascaray, "Quantum wells with zero valence band offset: drastic enhancement of forbidden excitonic transitions," Phys. Rev. B **54**, R11078 (1996).

G. Mohs, B. Fluegel, H. Giessen, K. Meissner, G. Khitrova, H. Gibbs, and N. Peyghambarian, "Ultrafast transient gain in type II multiple quantum wells," Appl. Phys. Lett. **68** (4), 511 (1996).

T. R. Nelson, Jr., J. P. Prineas, G. Khitrova, H. M. Gibbs, J. D. Berger, E. K. Lindmark, J.-H. Shin, E.-H. Shin, and Y.-H Lee, "Room-temperature normal-mode coupling in a semiconductor microcavity utilizing native-oxide AlAs/GaAs mirrors," Appl. Phys. Lett. **69**, 3031 (1996).

F. Jahnke, M. Kira, S. W. Koch, G. Khitrova, E. K. Lindmark, T. R. Nelson, Jr., D. V. Wick, J. D. Berger, O. Lyngnes, H. M. Gibbs, and K. Tai, "Excitonic nonlinearities of semiconductor microcavities in the nonperturbative regime," Phys. Rev. Lett. **77**, 5257 (1996).

J. Berger, S. Hallstein, O. Lyngnes, W. W. Rühle, G. Khitrova, and H. M. Gibbs, " Fast emission dynamics in a magneto-exciton quantum dot microcavity laser: breaking the phonon bottleneck," Phys. Rev. B Rapid Communications (to be published).

2. Scientific Personnel

Hyatt M. Gibbs, Professor
Galina Khitrova, Assistant Professor
Jill Berger, Graduate Student
Ove Lyngnes, Graduate Student
Sahnggi Park, Graduate Student

3. Inventions

None

4. Scientific Progress and Accomplishments 9/1/95-12/31/96

Phonon Bottleneck in Quantum-Dot Lasers. InGaAs/GaAs multiple quantum wells were grown which exhibit a large light-heavy hole splitting in zero magnetic field and well-resolved magnetoexciton Landau level transitions in a magnetic field exceeding 6 T. Three such quantum wells were grown in the center of a one-wavelength GaAs spacer of a vertical-cavity surface-emitting laser designed and grown for 4-K operation. Since the emission dynamics depend strongly on exciton-cavity detuning, the cavity mode was always tuned to the minimum threshold position, which varies with magnetic field due to the diamagnetic shift of the exciton. The same carrier density was achieved at each value of the field by adjusting the excitation power to maintain a constant total integrated emission. The delay time to maximum emission following fast excitation was measured with a streak camera. Even at 8 T, where the magnetoabsorption spectrum exhibits deep and well-resolved Landau levels, there is no increase in the delay. *Since there is no evidence of a phonon-bottleneck relaxation problem in these near-ideal magnetoexciton "quantum dots," it is concluded that there should be no phonon-bottleneck problem in exciting quantum-dot lasers*. This research has been accepted by *Physical Review B Rapid Communications*.

Nonlinear Behavior of Vacuum-Field Rabi Splitting in Semiconductor Microcavities. This research is assessing the use of vacuum-field Rabi splitting, sometimes called normal-mode coupling, for improving light extraction from light-emitting diodes. The reflection and transmission of microcavities with very large (>10) splitting-to-linewidth ratios were studied as a function of pump power. Unlike observations on low-ratio samples, the transmission peaks and reflection dips were found to disappear with increased pumping, at high enough pump power a single peak and a single dip appear close to the midpoint. This new nonlinear behavior occurs because of exciton broadening which is obscured by inhomogeneous broadening in other samples. As the pump increases, the exciton broadens (finally increasing the absorption at the peaks and reducing the transmission) with little change in oscillator strength (so the splitting does not change). We obtain excellent agreement between our data and a transfer matrix calculation of the microcavity transmission as a function of the measured nonlinear absorption of the exciton, using Kramers-Kronig transformation for the nonlinear refraction. A first principles many-body calculation of S. W. Koch and F. Jahnke (Marburg) is also in good agreement. These results on nonlinear normal-mode coupling were just published in *Physical Review Letters*.

The measurements above were performed at 4-K, but recently we have achieved record room-temperature normal-mode coupling using InGaAs/GaAs quantum wells in a microcavity with aluminum-oxide/GaAs mirrors. *Normal-mode coupling can be seen at moderate carrier densities even at room temperature.* The room-temperature normal-mode coupling was published in *Applied Physics Letters*.

Er-Doped Semiconductor Light Sources. The goal is to explore the use of a resonance between a quantum-well transition and an Er-ion transition to increase the efficiency of energy transfer. Last year weak 1.54-micron photoluminescence was reported from Er in an InGaAs/GaAs quantum well. This year slightly stronger photoluminescence was observed from Er grown into a GaAs/AlGaAs quantum well. *Secondary ion mass spectroscopy and absorption spectra show that Er causes interdiffusion resulting in the destruction of the quantum wells at high Er density.* Preliminary analysis of 1.5-1.6 micron photoluminescence spectra reveals three series of lines one of which can still be seen at 300 K. There is some evidence to suggest that these series are associated with defect states due to clusters consisting of Al ions around an Er ion.

5. Technology Transfer

Hyatt Gibbs visited Army Research Labs (George Simonis and Rich Leavitt) in January 1996 and Wright Laboratory (Robert Hengehold and John Loehr) in October 1995 and discussed the VCSEL and erbium research.

Meetings

G. Khitrova, "Vacuum rabi splitting in a semiconductor microcavity," KAIST, Taejon, Korea, July 28, 1995. Invited talk.

G. Khitrova, "Vacuum rabi splitting," NATO Workshop on Quantum Optics in Wavelength Scale Structures, Cargese, Aug. 29, 1995. Invited talk.

G. Khitrova, "Cavity QED," Philipps University, Marburg, Germany, December 14, 1995. Invited talk.

R. Jin, M. S. Tobin, R. P. Leavitt, H. M. Gibbs, G. Khitrova, F. Jahnke, S. W. Koch, and D. Boggavarapu, "Coulomb-enhanced luminescence decay in GaAs microcavity lasers," OSA/ILS Annual Meeting, 1995.

G. Khitrova, H. M. Gibbs, E. Lindmark, J. Prineas, S. Park, O.B. Gusev, M. S. Bresler, I. N. Yassievich, and V. F. Masterov, "Energy transfer from semiconductor quantum wells to Er^{3+}," APS **41** (1), 139 (1996).

D. Boggavarapu, D. McAlister, M. Anderson, M. Munroe, M. G. Raymer, G. Khitrova, and H. M. Gibbs, "Ultrafast photon statistics of normal mode coupling in a semiconductor microcavity," QTuA2, QELS '96.

G. Khitrova, "Normal mode coupling," Three lectures, April 10-12, 1996, Philipps University, Marburg, Germany. Invited talk.

H. M. Gibbs, G. Khitrova, J. D. Berger, D. Boggavarapu, E. K. Lindmark, O. Lyngnes, T. R. Nelson, Jr., S. Park, J. Prineas, D. V. Wick, K. Tai, R. Jin, M. S. Tobin, R. P. Leavitt, F. Jahnke, and S. W. Koch, "Quantum optics of semiconductor microcavities," MF1, IQEC'96, Sydney, Australia. Invited talk.

E. K. Lindmark, T. R. Nelson, Jr., G. Khitrova, H. M. Gibbs, A. V. Kavokin, and M. A. Kaliteevski, "Three coupled oscillators: normal mode coupling in a microcavity with two different quantum wells," MF4, IQEC'96, Sydney, Australia.

D. Boggavarapu, D. McAlister, M. Anderson, M. Munroe, M. G. Raymer, G. Khitrova, and H. M. Gibbs, "Photon number statistics in the strong coupling regime of semiconductor cavity QED," ML5, IQEC '96, Sydney, Australia.

J. Berger, O. Lyngnes, H. M. Gibbs, G. Khitrova, T. R. Nelson, E. K. Lindmark, J. Prineas, S. Park, A. V. Kavokin, M. A. Kaliteevski, and V. V. Zapasskii, "Magnetic field effects in semiconductor quantum-well microcavities," F07, IQEC'96, Sydney, Australia.

G. Khitrova, E. K. Lindmark, T. R. Nelson, D. V. Wick, J. Berger, O. Lyngnes, J. Prineas, S. Park, and H. M. Gibbs, "Nonlinear pump-probe measurements of semiconductor micro-cavities in the nonperturbative regime," IQEC '96, Sydney Australia.

O. Lyngnes, J. D. Berger, H. M. Gibbs, G. Khitrova, T. R. Nelson, D. V. Wick, E. K. Lindmark, K. Tai, J. Prineas, and S. Park, "Time resolved measurements of excitation density dependent normal mode coupling oscillation," IQEC '96, Sydney, Australia.

H. M. Gibbs, Ove Lyngnes, J. D. Berger, J. Prineas, S. Park, and G. Khitrova, "Nonlinear optics of semiconductor microcavities," NLO '96, Maui, Hawaii. (Invited talk).

T. R. Nelson Jr., G. Khitrova, E. K. Lindmark, D. V. Wick, J. D. Berger, H. M. Gibbs, and K. Tai, "Nonlinear cw pump-probe investigations for semiconductor microcavities exibiting normal-mode coupling," NLO '96, Maui, Hawaii.

G. Khitrova, "Nonlinear cw pump-probe and femtosecond reflectivity measurements of semiconductor microcavities exhibiting normal-mode coupling," Optical Properties of Mesoscopic Semiconductor Structures, Snowbird, May 7-10, 1996.

D. V. Wick, T. R. Nelson, Jr., E. K. Lindmark, H. M. Gibbs, G. Khitrova, and K. Tai, "Semiconductor microcavities in the strong coupling regime," OE/LASE '96. Invited talk.

D. V. Wick, T. R. Nelson, Jr., E. K. Lindmark, J. Prineas, O. Lyngnes, G. Khitrova, H. M Gibbs, "Enhanced spontaneous emission from a bulk semiconductor at room temperature," Th14, OSA/ILS Annual Meeting 1996.

M. V. Belousov, I. V. Ignatev, I. E. Kozin, G. Khitrova, H. M. Gibbs, and A. V. Kavokin, "Spectroscopic study of surface distribution of monolayer island formation of hetero-boundaries in the type-I GaAs/AlAs superlattices," International Symposium on Compound Semiconductors, St. Petersburg, Russia, September 23-27, 1996.

G. N. Aliev, V. A. Kosobukin, N. V. Luk'yanova, M. M. Moiseeva, R. P. Seisyan, G. Khitrova, and H. Gibbs, "Temperature broadening of exciton absorption lines and polaritonic processes in quantum wells of heterostructures (In, Ga)A/GaAs," International Symposium on Compound Semiconductors, St. Petersburg, Russia, September 23-27, 1996.

R. I. Dzhioev, H. M. Gibbs, E. L. Ivchenko, G. Khitrova, V. L. Korenev, M. N. Tkachuk, and B. P. Zakharchenya, "Exciton orientation-to-alignment conversion in type-II GaAs/AlAs superlattices," International Symposium on Compound Semiconductors, St. Petersburg, Russia, September 23-27, 1996.